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Research Article

Energy Effectiveness of Direct UV and UV/H_2O_2 Treatment of Estrogenic Chemicals in Biologically Treated Sewage

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Continuous exposure of aquatic life to estrogenic chemicals via wastewater treatment plant effluents has in recent years received considerable attention due to the high sensitivity of oviparous animals to disturbances of estrogen-controlled physiology. The removal efficiency by direct UV and the UV/H_2O_2 treatment was investigated in biologically treated sewage for most of the estrogenic compounds reported in wastewater. The investigated compounds included parabens, industrial phenols, sunscreen chemicals, and steroid estrogens. Treatment experiments were performed in a flow through setup. The effect of different concentrations of H_2O_2 and different UV doses was investigated for all compounds in an effluent from a biological wastewater treatment plant. Removal effectiveness increased with H_2O_2 concentration until 60 mg/L. The treatment effectiveness was reported as the electrical energy consumed per unit volume of water treated required for 90% removal of the investigated compound. It was found that the removal of all the compounds was dependent on the UV dose for both treatment methods. The required energy for 90% removal of the compounds was between 28 kWh/m^3 (butylparaben) and 1.2 kWh/m^3 (estrone) for the UV treatment. In comparison, the UV/H_2O_2 treatment required between 8.7 kWh/m^3 for bisphenol A and benzophenone-7 and 1.8 kWh/m^3 for ethinylestradiol.

1. Introduction

The present of estrogenic compounds in the environment and particularly the continuous exposure via wastewater treatment plant (WWTP) effluents have in recent years received considerable attention due to their damaging effects on the aquatic life [1–3]. The estrogenic compounds influence on the endocrine system, resulting in behavioural changes, changes in mating behaviour, and feminization of fish, and have even been linked to reduced sperm productivity in humans [4].

The synthetic steroid estrogen ethinylestradiol (EE2) is often found in low ng/L concentrations in WWTP effluents, and available data suggest that it is an important contributor to the estrogenic activity of WWTP effluents [2, 5–7]. The natural steroid estrogens, 17β-estradiol (E2), and estrone (E1) are also considered important contributors to the estrogenic activity of WWTP effluents. They are less potent than EE2 but are typically found in slightly higher concentrations. Other known contributors to the estrogenic effect are industrial phenols such as nonylphenol (NP), octylphenol (OP), bisphenol A (BPA), and compounds used in personal care products such as parabens and benzophenones. These are typically found in the μg/L concentration range [7–11]. However, these compounds have considerably lower estrogenic activity compared to steroidal estrogens [11, 12].

Degradation of some of these estrogenic compounds by UV photolysis and the advanced oxidation process UV/H_2O_2 in laboratory setups has been reported in the literature [13–17].

Degradation by photolysis and radical oxidation initiated by the UV/H_2O_2 treatment are thus known processes for some estrogens in wastewater. However, the present literature does not give the data needed for estimating the treatment intensity required for treatment of real wastewater since they do not consider realistic flow through conditions, radical scavengers, and the shadow effect seen in real wastewater. Thus, the size of the treatment system and the expected running cost of the treatment if the techniques were applied as a real treatment cannot be found in the literature.

Therefore, this work has used an experimental setup with realistic dimensions from a UV treatment plant intended for disinfection of a wastewater treatment plant effluent by medium pressure UV lamps. With this setup, the removal efficiency by direct UV and the advanced oxidation process UV/H_2O_2 of estrogenic compounds were investigated in tap water and biologically treated sewage. The results of the experiments are reported in units of energy applied for the treatment as recommended by IUPAC [18].

2. Method

2.1. Regents and Materials. All the investigated estrogenic compounds (see Table 1) were purchased from Sigma-Aldrich. Methanol, acetone, and heptane together with 35% hydrogen peroxide, potassium titanium oxide oxalate dihydrate, sodium phosphate monobasic dehydrate, and 85% orthophosphoric acid were obtained from Sigma-Aldrich as well. The chemicals for derivatisation of the steroid estrogens (dithioerythritol, trimethylsilyl imidazole, and N-methyl-N-(trimethylsilyl)-trifluoroacetamide) were purchased from Sigma-Aldrich. All chemicals were of analytical grade except potassium titanium oxide oxalate dihydrate which was of technical grade.

The water used for experiments was wastewater effluent from Usserød Wastewater treatment plant (Hørsholm, Denmark). The water was stored in the dark at 10°C until experiments were performed. The effluent was used for experiment within 3 days after the collection, however once after 12 days as an exception. The water was poured into three 25 L plastic containers and spiked with the mixed solutions so the concentrations of xenoestrogens and steroid estrogens were 1 μg/L and 400 ng/L, respectively. In the experiment with UV/H_2O_2, the hydrogen peroxide (35% solution) was added, so the desired concentration was achieved.

Tap water used in experiments to investigate the matrix effect in comparison with wastewater was from the DTU-Lyngby Campus. This water is not chlorinated, and it has a content of mayor ions similar to the wastewater, but a low concentration of organic matter since it is taken from a deep well (more than 50 years old groundwater).

2.2. Bench-Scale Reactor. The treatments were carried out in a bench-scale, flow-through photoreactor (see Figure 1). The lamp (700 W, Bau47, Scan Research A/S, Herning, Denmark) is located coaxial in the centre of the reactor. The UV lamp was placed inside a quarts sleeve which is pumped with an inert gas to avoid ozone production. The distance from the lamp to the inner side of the reactor is 5.7 cm. A spectrum of the output of the lamp is shown in supporting information of a previous paper [19].

Figure 1 shows a schematically drawing of the experimental setup. The water was pumped from the plastic containers through a flowmeter and into the reactor at the bottom. A valve was used to adjust the flow rate. The samples for analysis were taken from the outlet after one retention time and from the containers (inlet concentration). The blind sample was taken before spiking and addition of hydrogen peroxide. The samples were acidified with phosphate buffer (pH = 3) as preservative except samples for measurement of hydrogen peroxide concentration.

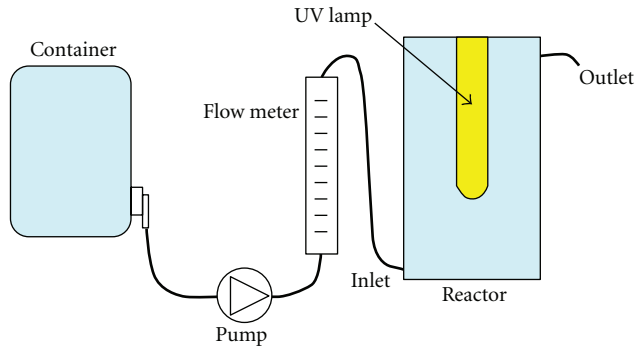

Figure 1: Diagram of the experimental setup.

2.3. Sample Preparation for Chemical Analysis and YES Assay. For each experiment, three samples of 500 mL each were analysed. Surrogate standard was added to every sample before solid-phase extraction (SPE) to compensate for possible losses during sample preparation and analysis. The extractions were performed at commercial packed cartridges (500 mg C18 adsorbent/6 mL cartridge, Supelco), which were conditioned with 2 × 1.5 mL heptane, 1 × 1.5 mL acetone, 2 × 1.5 mL methanol, and 2 × 1.5 mL acidified water (phosphate buffer, pH = 3) before the extraction begins. The water was transmitted to the SPE column by means of vacuum with a flow rate at maximum 5 mL per minute. Afterwards, the column is dried for approximately 1 hour until complete dryness. The samples were eluted with acetone until 5 mL eluent was collected in a test tube. Then the eluent was dried under a stream of nitrogen in a thermostat-controlled heating block to almost completely dryness.

The samples for YES assay, to which no surrogate standard was added, were dissolved in ethanol, while the samples for chemical analysis were further purified as described in the following. One gram of 1% deactivated silica gel (silica gel 60, 0.063–0.200 mm (70–230 mesh ASTM) Merck) was suspended in 3 mL heptane-acetone mixture (65 : 35) and poured into 3 mL glass cartridge. The almost dried samples were resolved in approximately 0.3 mL heptane acetone mixture (65 : 35) and transferred to the top of the silica gel. The test tube was washed with little more of the solvent mixture to minimize the loss of sample. Then glass cartridge containing silica gel and sample was eluted with heptane acetone mixture (65 : 35) until approximately 5 mL eluent was collected. Once again the solvent was evaporated under a stream of nitrogen, but this time to complete dryness. The samples were dissolved in 250 μL heptane acetone mixture and transferred to a GC vial (300 μL, Chromacol) [8, 11, 20].

2.4. Quantification of Xenoestrogens. The analysis of the estrogens was performed by gas chromatography using a

Table 1: The electrical energy per order, EEO, (kWh/m^3) for UV and UV/H_2O_2 treatments of the investigated compounds in treated wastewater from Usserød WWTP. 95% confidence intervals are indicated.

	UV	UV/H_2O_2
Parabens		
Methylparaben (MP)	13.9 ± 0.2	8.1 ± 0.6
Ethylparaben (EP)	15.9 ± 0.7	5.3 ± 0.3
Propylparaben (PP)	19.1 ± 1.1	6.4 ± 0.4
isoButylparaben (isoBP)	14.2 ± 1.6	7.0 ± 0.4
Butylparaben (BP)	28.0 ± 2.9	7.9 ± 0.4
Industrial phenols		
Bisphenol A (BPA)	16.1 ± 1.9	8.7 ± 1.2
isoNonylphenol (isoNP)	11.5 ± 2.6	7.6 ± 1.2
Octylphenol (OP)	8.1 ± 1.6	2.6 ± 0.1
Sunscreen chemicals		
Benzophenone-3 (BP-3)	25.4 ± 1.3	8.5 ± 0.6
Benzophenone-7 (BP-7)	21.1 ± 1.4	8.7 ± 0.5
Octyl methoxycinnamate (OMC)	19.8 ± 2.2	7.1 ± 1.2
Homosalate (HMS)	15.0 ± 1.6	7.7 ± 0.6
3-(4-Methylbenzyliden)camphor (4-MBC)	17.3 ± 2.2	5.0 ± 0.1
Octyl dimethylaminobenzoate (OD-PABA)	4.2 ± 0.7	4.1 ± 0.1
Steroid estrogens		
Estrone (E1)	1.2[a]	N.D.
17β-estradiol (β-E2)	4.9 ± 0.8	2.2 ± 0.2
Ethinylestradiol (EE2)	6.1 ± 0.7	1.8 ± 0.03
Estrogenic potency		
Estradiol equivalent concentration (EEC) according to YES assay	4.9 ± 1.0	N.D.

N.D.: no data. [a]Regression with only two points.

Varian 3800 GC coupled to Varian Saturn 2000 Ion trap (MS-MS). The column used was a Varian, FactorFour capillary column (VF-5 ms, 30 m × 0.25 mm ID DF = 0.25) with a gas flow of 1 mL/min. Seven and half μL sample was injected using Varian 8200 Autosampler in split/splitless injection mode with the Varian 1079 injection gate.

The GC oven temperature was maintained at 100°C for 1 min and then programmed at 20°C/min to 110°C, then at 10°C/min to 250°C, followed by 25°C/min to 285°C, and finally 35°C/min to 320°C, which was held for 7.1 min to ensure that most of other organic compounds also came out. Each compound was quantified based on a characteristic daughter ion of MS-MS spectroscopy, and the other daughter ions were used for confirmation of the identity of the detected chemicals [8, 11, 20].

2.5. Quantification of Steroid Estrogens. After the analysis of parabens, and so forth, the remaining extract of the samples was transferred to 3 mL reactival, and the GC-vials were washed one or two times with acetone to ensure complete transferring of the sample. The samples were dried under nitrogen to complete dryness. Derivatisation mixture was made by mixing 2 mg dithioerythritol (DTE), 2 μL trimethylsilylimidazole (TMSI), and 1000 μL N-methyl-N-(trimethylsilyl)-trifluoroacetamide (MSTFA). To the derivatisation vials, 50 μL of that mixture was added and caped in order to be shaken. The vials were placed in an oven at 60°C for 60 min. Afterwards, the vials were placed at the thermostat-controlled heating block and evaporated to dryness under stream of nitrogen. The samples were dissolved in 250 μL heptane and transferred to GC vials again. The GC oven temperature was maintained at 80°C for 1 min and then programmed at 25°C/min to 230°C, followed by 1°C/min to 248°C, and finally 45°C/min to 320°C, which was held for 3 min to ensure that all interfering compounds were eluted from the column. The method used specific MS/MS parameters and was based on a method evaluation described by Andersen et al. [21].

The range of quantification was for xenoestrogen in general between 0.005 and 1.0 μg/L and typically between 2 and 500 ng/L for the steroid estrogens. The sample preparation and method performance were evaluated in the interlaboratory comparison described by Heath et al. [22].

2.6. YES Assay. The extracts were serially diluted in a growth media for yeast cells. The dilutions were incubated with an estrogen-responsive yeast cell for 72 h. The estrogenic effect was quantified by measuring the development of a red dye which is produced by the yeast cells with an enzyme and is produced proportionally to the estrogenic concentration in the cells. For quantification of the estrogenic effect, a standard curve was made from a stock solution of 17β-estradiol (E2). The method for quantifying the estrogenic potency of the extracts is generally based on the method

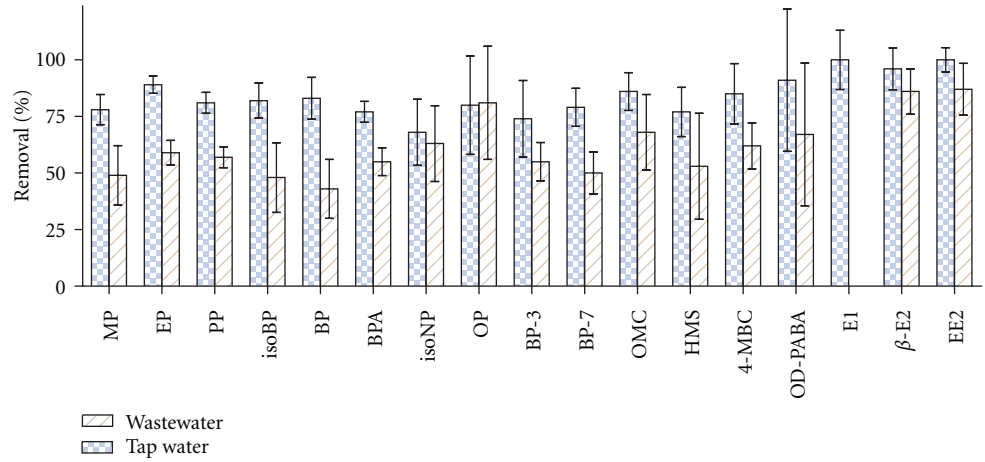

Figure 2: The removal of estrogenic compounds from tap water and wastewater effluent by UV/H_2O_2. The electrical energy dose was 1.8 kWh/m^3, and the initial concentration of hydrogen peroxide was 60 mg/L. The error bars present the 95% confidence interval.

introduced by Routledge and Sumpter [23]. Details of the method variation are described in Hansen et al. [20] and Kusk et al. [11].

2.7. Experiments. Three different types of experiments were performed. First, the effect of concentration of hydrogen peroxide in wastewater on removal of estrogens with an UV dose equivalent to an energy use of 1.8 kWh/m^3 was investigated. Second, the influence of the high concentration of different matrix components was investigated by comparing the removal of estrogens in experiments with either the wastewater effluent or tap water with the optimized hydrogen peroxide dose of 60 mg/L and an UV dose equivalent to an energy use of 1.8 kWh/m^3. Finally, experiments were performed in wastewater with or without addition of 60 mg/L hydrogen peroxide using different UV doses equivalent to an energy use ranging from 1.75 to 10.9 kWh/m^3 or from 2.3 to 16.3 kWh/m^3, respectively.

2.8. Data Treatment. The treatment effectiveness was evaluated based on the electrical energy per order (EEO; unit kWh/m^3), which is defined as the electrical energy consumed per unit volume of water treated required for 90% removal of the investigated compound [18]

$$\log\left(\frac{C}{C_i}\right) = \frac{-1}{\text{EEO}} \cdot \text{EED}, \quad (1)$$

where C_i and C are the initial and the final concentrations, respectively, EED is the electrical energy dose in kWh/m^3, and EEO is the electrical energy per order. The normalised concentration of the investigated chemicals was plotted against the electrical energy dose. Constructed plots were used for determination of the EEO by least square fit according to (1). In some cases, concentration below the limit of quantification was used in the estimation of EEO if a good analytical signal was found with correct ratios between the daughter ions in the mass spectra.

3. Results and Discussion

The UV treatment intensity was characterised by the electric energy consumption. This was done according to recommendation by IUPAC [18]. Since the lamp was completely submerged, all irradiation emitted by the lamp was absorbed by the water, and thus, the electrical energy dose (EED) at each treatment level was calculated as the energy consumption of the lamp divided by the flow rate of the wastewater.

The absorbance of the spiked tap and wastewater was measured on UV-vis spectrophotometer (Cary 50 Bio, Varian), and the spiking of the water did not change the absorbance of the water in the UV and visible range (800–190 nm), even though the water was spiked with 17 different chemicals. The UV dose, each compound was exposed to, is therefore considered as independent of the other compounds.

3.1. The Effect of Water Matrix on the Removal by UV/H_2O_2. A single experiment was done in tap water to compare the efficiency of UV/H_2O_2 treatment in different water matrix. Figure 2 shows the removal of the compound in tap water and wastewater effluent with an initial concentration of hydrogen peroxide of 60 mg/L and UV dose equivalent to an energy use of 1.8 kWh/m^3. The removal of estrogenic chemicals is higher in tap water than in wastewater effluent. This is due to higher concentrations of other organic materials than the spiked compound in the wastewater effluent compared to tap water. These can act as scavengers of $^{\bullet}$OH radicals and result in a shadowing effect, where the compound either blocks the pathway of the light or adsorbs the light.

Furthermore, more of the hydrogen peroxide was activated in the tap water (21%) than in the wastewater (11%), which may be a result of less shadowing effect in the tap water resulting in a larger amount of the light being used for photolysis of hydrogen peroxide. Neamțu and Frimmel [15] found the same tendency when they investigated the removal of BPA.

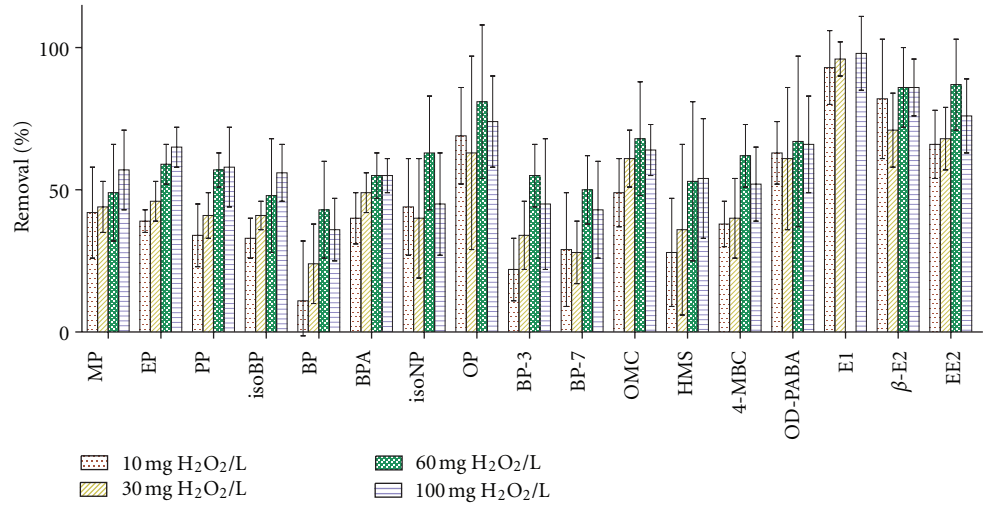

Figure 3: The removal of estrogens in wastewater effluent at varying concentrations of hydrogen peroxide at constant energy dose (1.8 kWh/m^3). The error bars present the 95% confidence interval.

3.2. The Effect of H_2O_2 Concentration on the Removal of Chemicals. The removal of the investigated compounds increased with increasing hydrogen peroxide concentration until 100 mg/L where the removal of most of the compound decreased again (Figure 3). The removal was expected to decrease again at higher concentration due to larger possibility for the hydroxyl radical to react with hydrogen peroxide and form the less reactive $HO_2^{\bullet}$. An inhibition of the degradation of chemicals at high concentration of hydrogen peroxide was found during the study of Neamțu and Frimmel [15] as well.

3.3. Removal. The obtained removal of all investigated compounds is shown in Figures 4 and 5. The more UV irradiation the water was exposed to (higher EED), the higher the removal of the compounds was. When the results from UV and UV/H_2O_2 treatment with an electrical energy dose of 2.3 kWh/m^3 are compared, it is seen that a higher removal was obtained at UV/H_2O_2 treatment than only UV irradiation.

In the case of UV/H_2O_2 treatment, the removal seems more similar than in treatments with UV. With an EED of 2.3 kWh/m^3, the removal was within the range of 51% to 95% (51 to 86 without steroid estrogens), while the range is from 20% to 99% for UV treatment. This may be due to that the mechanism of the removal with $^{\bullet}$OH radicals is nonselective, while the UV treatment depends upon the absorbance and quantum yield, which varies is a discrete property of each compound. The results of estrone (E1) are missing in Figure 4 due to analytical error. The increased removal when hydrogen peroxide was added is consistent with results obtained by Neamțu and Frimmel [15] and Chen et al. [14].

The estrogenic activity of the wastewater effluent treated by UV was measured by YES assay and was found to be 380 ng/L 17β-estradiol equivalents for the spiked wastewater and 15 ng/L 17β-estradiol equivalents for the lowest treatment intensity (2.3 kWh/m^3). Thus, even after the lowest treatment, almost all of the estrogenic activity was removed, and for the following treatments, some estrogenic activity was detected but below the quantification limit.

3.4. Electrical Energy Efficiency. As described in Section 2.8, the normalised concentration of the investigated chemicals was plotted against the electrical energy dose (Figure 6). The values of the EEO for the UV treatment were in the range 1.2–28.0 kWh/m^3 (Table 1). The compounds with lower values of EEO are easier to degrade than the one with higher value. The estrone (E1) was very sensitive towards UV light and has an EEO at 1.2 kWh/m^3. At the lowest treatment level (2.3 kWh/m^3), 99% of estrone was removed, and thus, the regression was made with only two points.

As mentioned, the addition of hydrogen peroxide to the UV treatment resulted in increased removal of the investigated compounds and thus lower energy consumption and lower EEO values (Table 1). Another benefit from addition of hydrogen peroxide was more uniform values of EEO for the investigated compounds. So the compounds with EEO values between 11.5 and 28 kWh/m^3 for UV treatment had a reduction of EEO to approximately 7-8 kWh/m^3 when adding 60 mg/L hydrogen peroxide.

For UV treatment, butylparaben (BP) was the chemical which was most difficult to be removed (EEO = 28.0 kWh/m^3), while for UV/H_2O_2, it was BPA and BP-7 (EEO = 8.7 kWh/m^3). Estrone (E1) would probably be the one that required the smallest amount of energy according to the tendency, but data is missing due to problem with the analysis. The lowest EEO obtained for the UV/H_2O_2 treatment was 1.8 kWh/m^3 (EE2).

The EEO for removal of estrogenic activity was estimated for UV treatment only and was in the same range as the EEOs obtained for 17β-estradiol and ethinyl estradiol. Thus, the measured estrogenic activity is mainly due to the two estrogens E2 and EE2. A previous study with Milli-Q water and approximately 5000-fold higher EE2 concentration removed the estrogenic activity (by YES assay) with the same rate as

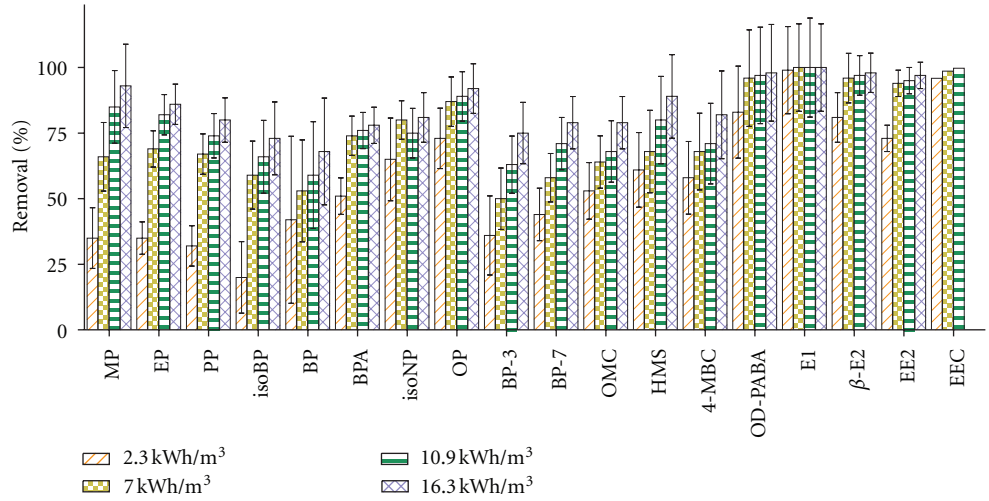

Figure 4: The removal of estrogenic compounds from wastewater effluent by photolysis. The error bars present the 95% confidence interval. The abbreviation can be found in Table 1.

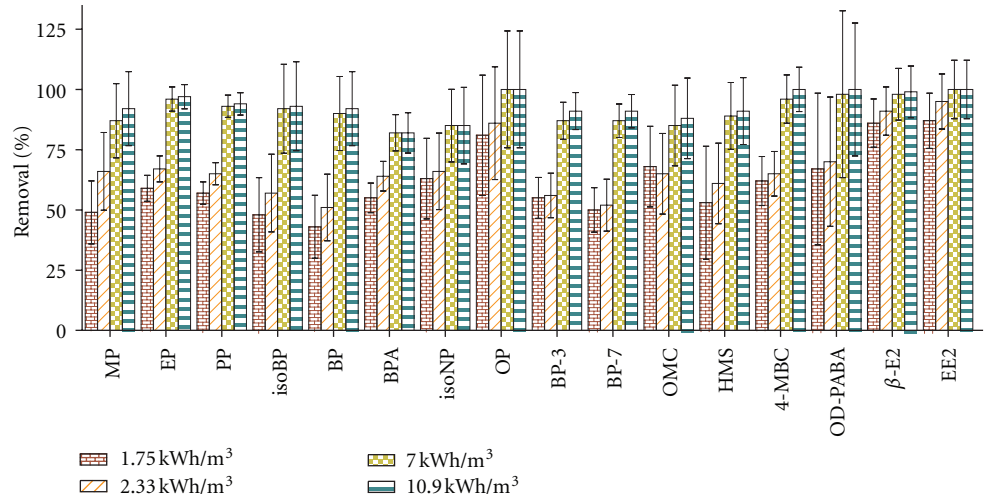

Figure 5: The removal of estrogenic compounds from wastewater effluent by UV/H_2O_2. The initial concentration of hydrogen peroxide was 60 mg/L. The error bars present the 95% confidence interval. The abbreviation can be found in Table 1.

their removal of EE2 by treatment with low-pressure UV and H_2O_2 [16]. Another study [20] was able to remove estrogenic activity by the same rate as the estrogenic compounds by ozonation, which is partially a radical oxidation reaction similar to the UV/H_2O_2 treatment. Consequently, the by-products formed from estrogenic compounds during UV and UV/H_2O_2 treatment do not have estrogenic activity.

3.5. Considerations on Economical Feasibility and Energy Efficiencies. The investigated compounds were all removed by direct UV and UV/H_2O_2. To consider the possibility of these methods to be applied in the wastewater treatment, the energy cost is compared to the current treatment cost.

The Danish Water and Wastewater Association has collected data from a number of treatment plants and calculated the cost of treating 1 m^3 wastewater. The Danish WWTPs can be divided into three groups depending on the size. Large treatment plants treat water from what corresponds to more than 100.000 person equivalent (PE), while medium-sized treatment plants are between 20.000 and 100.000 PE. The small treatment plants treat less than 20.000 PE. The average cost of treating 1 m^3 of wastewater in 2001 was 0.21 € and 0.27 € for large and medium treatment plans, respectively [24]. For small plant, the cost is approximately doubled (0.46 €/m^3). The wastewater treatment plants pay 0.11 €/kWh.

A stream containing numerous contaminants in low concentration requires an energy dose corresponding to the energy needed to remove the most resistant one [25]. For the estrogenic compounds, the most resistant chemical was BP with an EEO value of 28 kWh/m^3 when wastewater was treated with UV irradiation alone. By UV/H_2O_2, BPA and BP-7 required the highest amount of energy to be degraded (EEO = 8.7 kWh/m^3).

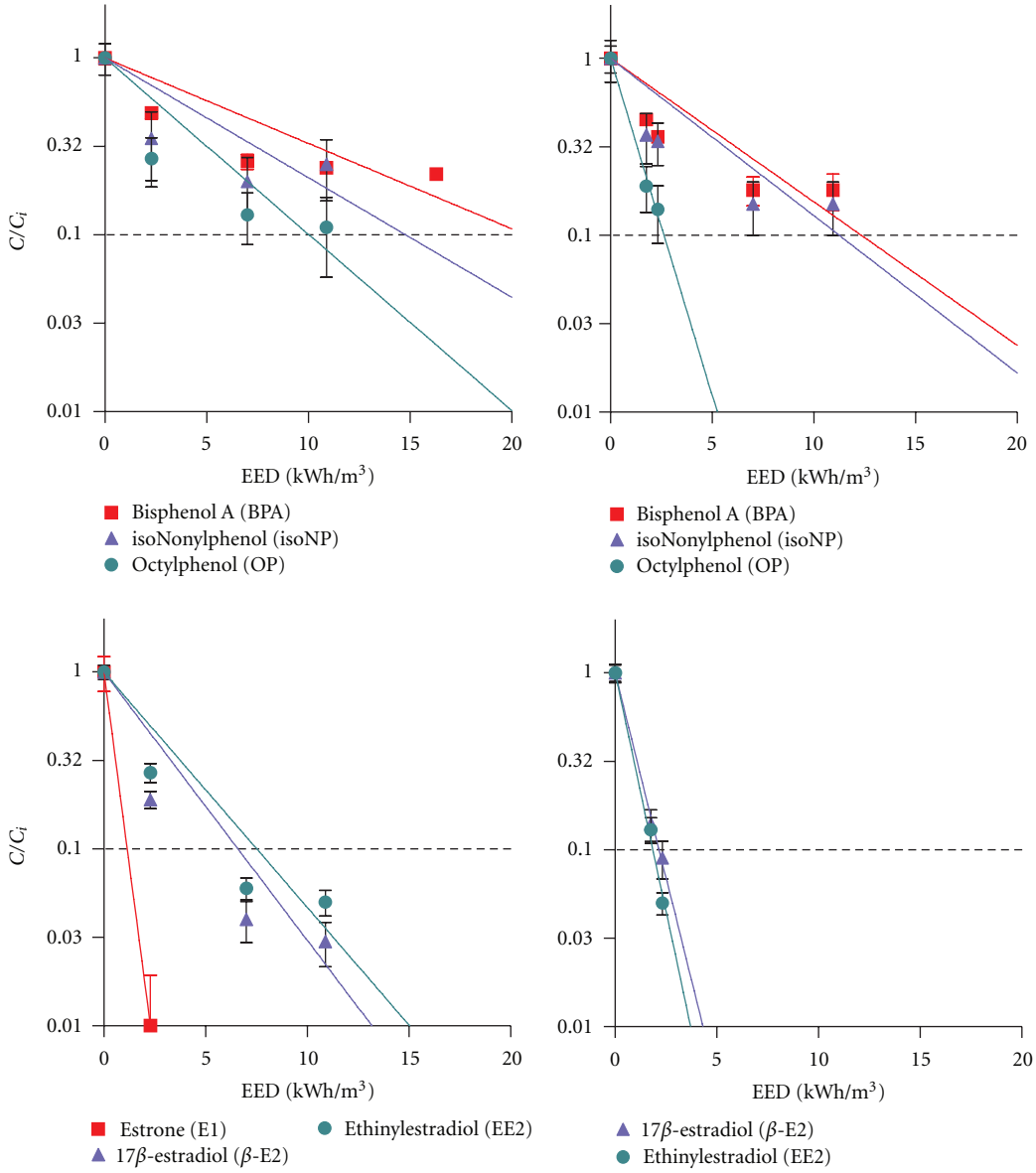

Figure 6: Degradation of selected estrogenic chemicals. Left: direct UV treatment. Right: UV/H_2O_2 treatment with a hydrogen peroxide concentration of 60 mg/L.

Addition of hydrogen peroxide reduced the energy consumption by approximately a factor of three which would be economically advantageous considering the price of electric energy and hydrogen peroxide in Denmark. A treatment with an electrical energy dose of 8.7 kWh/m^3 would remove 90% of the most resistant chemicals, whereas it will require 17.4 kWh/m^3 if the chemicals need to be removed by 99%.

Steroid estrogens are generally considered to be responsible for the majority of estrogenicity in WWTP effluents [6, 7]. Supposing only 90% removal of the steroid estrogens is required in order to achieve an acceptable water quality, a considerable energy reduction would be possible, since the steroid estrogens require less treatment. By the UV/H_2O_2 treatment, the most resistant of the steroid estrogens (E2) requires 2.2 kWh/m^3 to obtain 90% removal. At this level of treatment, the removal of the other compound with EEO in the range of 7-8 kWh/m^3 will be approximately 50% (calculated using (1)).

The cost of a treatment can be found by multiplying the cost of electricity with the value of EEO. Thus, the treatment with high energy consumption would cost 0.93 €/m^3, and if only the steroid estrogens should be removed, the cost of the electrical energy would be 0.24 €/m^3. Beside the cost of electricity, there will also be expenses for hydrogen peroxide and maintenance of equipment.

Comparing with alternative treatment solutions, the current best option for polishing wastewater for estrogenic chemicals is ozonation [20, 26–28]. The EEO for the same estrogenic chemicals, as are the subject of this paper, in treated wastewater from the same source, was described by

Hansen et al. [20]. In that study, the energy required to remove each estrogen by 90% with ozonation, when the energy to produce ozone and the energy required to produce the pure oxygen that is used by the ozone generator was also considered, was 0.14–0.90 kWh/m^3. In the same study, an effluent from another source that had a higher COD and UV-absorbance required energy in the range of 0.22–1.09 kWh/m^3 for removing the estrogens [20].

4. Conclusions

It was found that the water matrix influenced the removal of the investigated compounds. The organic and inorganic substances in wastewater acted as scavenger compound for the $^{\bullet}$OH radicals and blocked the pathway of the UV light. Furthermore, it was found that it is important to optimize the concentration of hydrogen peroxide, since a too low concentration of hydrogen peroxide results in decreased removal of the estrogenic chemicals, while a high hydrogen peroxide concentration may result in a decreasing degradation due to the formation of the less reactive $HO_2^{\bullet}$ radical.

Moreover, it was found that all estrogenic chemicals could be removed by photolysis with varied energy effectiveness and that UV/H_2O_2 reduced the spread between the energy effectiveness of removing the chemicals and lowered the electrical energy dose. Addition of an optimized concentration of hydrogen peroxide reduced the energy consumption by 2-3-fold, which would be economical considering the price of energy and the chemical in Denmark.

In general, it was found that the parabens, the industrial phenols, and the sunscreen chemicals required much higher UV dose than the steroid estrogens. BP was the estrogenic compound that required the highest UV dose to be degraded by direct photolysis, while by UV/H_2O_2, it was BPA and BP-7. Steroid estrogens, which are generally considered to be responsible for the bulk of estrogenicity in WWTP effluents, required the least amount of treatment for removal.

Considering only the energy consumption for the treatment, both UV and UV/H_2O_2 are considerable less effective solutions for removal of estrogenic chemicals in biologically treated wastewater compared to ozonation.

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